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Mesospheric dynamical changes induced by the solar proton events in October–November 2003

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[1] The Thermosphere Ionosphere Mesosphere Electrodynamic General Circulation Model (TIME-GCM) was used to study the atmospheric dynamical influence of the solar protons that occurred in Oct–Nov 2003, the fourth largest period of solar proton events (SPEs) measured in the past 40 years. The highly energetic solar protons produced odd hydrogen (HO_x) and odd nitrogen (NO_y). Significant short-lived ozone decreases (10–70%) followed these enhancements of HO_x and NO_y and led to a cooling of most of the lower mesosphere. Temperature changes up to ±2.6 K were computed as well as wind (zonal, meridional, vertical) perturbations up to 20–25% of the background winds as a result of the solar protons. The solar proton-induced mesospheric temperature and wind perturbations diminished over a period of 4–6 weeks after the SPEs. The Joule heating in the mesosphere, induced by the solar protons, was computed to be relatively insignificant for these solar storms. **Citation:** Jackman, C. H., R. G. Roble, and E. L. Fleming (2007), Mesospheric dynamical changes induced by the solar proton events in October–November 2003, *Geophys. Res. Lett.*, *34*, L04812, doi:10.1029/2006GL028328.

1. Introduction

[2] Several very large solar eruptive events in late October and early November 2003 resulted in huge fluxes of charged particles at the Earth [*Mewaldt et al.*, 2005]. Much of the energy was carried by solar protons, which impacted the middle atmosphere (stratosphere and mesosphere) leading to ionizations, dissociations, dissociative ionizations, and excitations. The proton-induced atmospheric interactions resulted in the production of odd hydrogen, HO_x (H, OH, HO_2), and odd nitrogen, NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, HONO, $ClONO_2$, $ClNO_2$, $BrONO_2$) constituents either directly or through a photochemical sequence [e.g., *Swider and Keneshea*, 1973; *Crutzen et al.*, 1975]. There were a few periods from 26 Oct.–7 Nov., 2003, when the proton fluxes increased dramatically beyond background levels for 1–3 days. These periods are known as solar proton events (SPEs) and some of the middle atmospheric constituent influences during these SPEs have been discussed before [e.g., *Jackman et al.*, 2005a; *Verronen et al.*, 2005]. These Oct./Nov. 2003 SPEs were very intense and were computed to be the fourth largest SPE period in the past 40 years [*Jackman et al.*, 2005b].

[3] We are not aware of any measured atmospheric dynamical changes during these very significant atmospheric perturbations, however, past studies [*Banks*, 1979; *Reagan et al.*, 1981; *Jackman and McPeters*, 1985; *Roble et al.*, 1987; *Reid et al.*, 1991; *Zadorozhny et al.*, 1994; *Jackman et al.*, 1995; *Krivolutsky et al.*, 2006] have suggested that very large SPEs can lead to temperature changes through ozone depletion and/or Joule heating.

[4] In this paper, we used the latest version of the TIME-GCM (Thermosphere Ionosphere Mesosphere Electrodynamics – General Circulation Model) [*Roble*, 2000], which contains both ozone photochemistry and auroral particle and Joule heating, to study the influence of the very large proton fluxes during Oct./Nov. 2003 on the temperature and winds of the middle atmosphere. The TIME-GCM allowed us the opportunity to compare and contrast the different atmospheric perturbations during SPEs that lead to temperature and wind changes. We will focus on a snap-shot output from the model for one day, 30 October 2003, at 0:00 UT near a period of maximum solar proton flux to investigate these effects.

2. Model Description and Solar Proton Caused Constituent Change

[5] The TIME-GCM was first described by *Roble and Ridley* [1994]. This model has an effective 5° latitude × 5° longitude grid with 45 constant pressure surfaces in the vertical between approximately 30 and 500 km altitude with a vertical resolution of 2 grid points per scale height and a model time step of 5 minutes. The TIME-GCM has a comprehensive set of physical, chemical, and dynamical processes included to simulate the upper atmosphere and ionosphere. A detailed description of the model and its components is given by *Roble* [2000].

[6] The model is forced at its lower boundary of 10 hPa by global geopotential height and temperature distributions from NCEP (National Centers of Environmental Prediction) analysis. This feature provides the ability to simulate particular periods of interest, such as 27 October through 11 December 2003 for this specific study [e.g., *Liu and Roble*, 2005].

[7] We use the proton flux data provided by the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC) for the NOAA Geostationary Operational Environmental Satellites (GOES) (see http://sec.noaa.gov/Data/goes.html). The GOES 11 data are considered to be the most reliable of the current GOES datasets for the proton fluxes depositing energy into polar latitudes and were used as the source of protons in several

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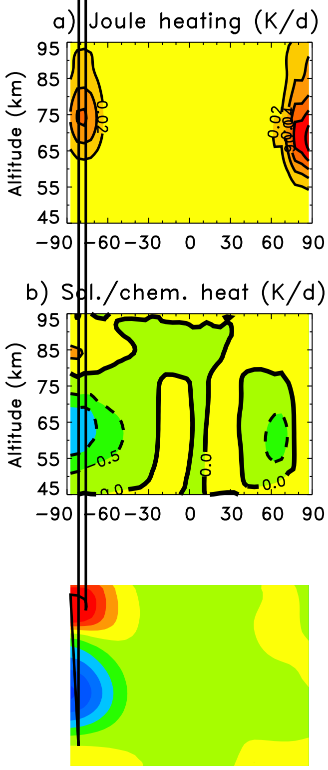


pression caused by enhanced downward winds (or reduced upward winds, see Figure 3a and discussion in section 4). We computed a zonal average adiabatic heating increase in the upper polar southern mesosphere with a maximum of +2.3 K/d near 85–90 km at 0:00 UT on 30 October 2003 due to circulation changes driven by the SPE-caused ozone reductions below 80 km (see Figure 3b). Other computed adiabatic heating changes were smaller at lower southern and all northern latitudes. The Equatorial cooling above 85 km was caused by enhanced upwelling.

[18] SPE-caused enhancements in atomic oxygen in the southern polar upper mesosphere will lead to more O-CO_2 collisions which will result in more excited CO_2 molecules, another radiatively active gas, and more cooling. We compute a zonal average maximum increase in the cooling rate of +0.8 K/d (from ~7.5 K/d to ~8.3 K/d) near 90–95 km, 90°S at 0:00 UT on 30 October 2003 due to the SPEs (not shown). Computed cooling rate change from either ozone depletion or excited CO_2 enhancement was much smaller in the northern hemisphere.

4. Computed Dynamical Changes

[19] Dynamical (temperature and wind) changes have long been associated with SPEs. Temperature decreases of 1–10 K were computed to follow from very large SPEs in several studies [*Reagan et al.*, 1981; *Jackman and McPeters*, 1985; *Roble et al.*, 1987; *Reid et al.*, 1991; *Zadorozhny et al.*, 1994; *Jackman et al.*, 1995; *Krivolutsky et al.*, 2006]. Large temperature decreases of 14 K near 50 km were deduced as a result of a meteorological rocket campaign during the huge Oct. 1989 SPEs [*Zadorozhny et al.*, 1994]. *Krivolutsky et al.* [2006] derived temperature decreases of 10 K near 65 km and increases of 10 K near 80 km using UARS HALOE measurements during the very large July 2000 SPE. *Kubo et al.* [2003] deduced temperature increases near 93 km of 8 K as a result of the July 2000 SPE with the Svalbard Radar.

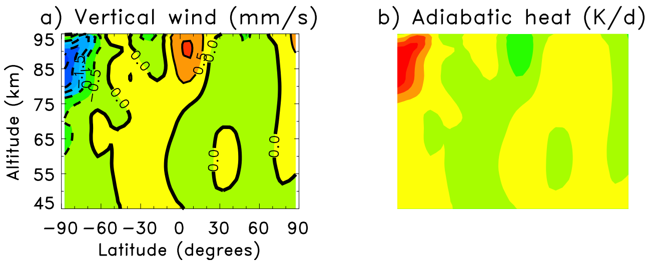
[20] The heating and cooling rate changes ultimately led to calculated temperature variations as a result of the Oct./Nov. 2003 SPEs. The largest temperature changes in the lower to middle mesosphere were driven by the ozone decreases, which forced both heating and cooling rate changes. The heating rate reductions dominated the effect and resulted in temperature decreases of a zonal average maximum of −2.6 K on 30 Oct. 2003 near 65 km, 90°S (see Figure 2c). Most of the middle and high latitude mesosphere was dominated by decreases in temperature. These computed temperature decreases were modest compared to those measured for other very large SPEs [*Zadorozhny et al.*, 1994; *Krivolutsky et al.*, 2006], however, they are similar to several other model computations [*Reagan et al.*, 1981; *Jackman and McPeters*, 1985; *Roble et al.*, 1987; *Reid et al.*, 1991; *Jackman et al.*, 1995].

[21] Net heating rate increases due to adiabatic heating and cooling rate increases caused by enhanced CO_2 excitation were of significance in the upper mesosphere. The adiabatic heating change dominated and resulted in predicted temperature increases of a zonal maximum of +2.5 K on 30 Oct. 2003 near 90 km, 90°S (see Figure 2c). These computed temperature increases were smaller than those deduced from measurements during another very large SPE, the so called Bastille Day storm of July 2000 [*Kubo et al.*, 2003; *Krivolutsky et al.*, 2006].

[22] The predicted temperature changes are mainly concentrated in the sunlit southern hemisphere and were very small in the northern hemisphere. The maximum temperature changes are about a 1–2% variation compared with the background temperature distribution.

[23] Other dynamical changes including variations in mesospheric winds have been observed associated with SPEs in 1982, 1984, and 1989 [*Rottger*, 1992; *Johnson and Luhmann*, 1993]. The model computed zonal, meridional, and vertical winds were all perturbed as a result of the Oct./Nov. 2003 SPEs. The zonal wind was forced to be more westerly by the SPEs resulting in a zonal average maximum speed change of 2.4 m/s on 30 Oct. 2003 near 80 km, 65°S (not shown). These changes were modest when compared with the background and amounted to a maximum change of about 20% in the SH, primarily opposing the prevailing easterlies at this time of year.

[24] The meridional wind was forced to be generally more southerly in the SH resulting in a zonal average maximum speed change of −0.8 m/s on 30 Oct. 2003 near 95 km, 65°S (not shown). These changes were modest compared with the background and amounted to about a 20–25% change near the SH mesopause, primarily opposing the general northerly flow at this time of year.



[25] The vertical wind was forced to be more downward in the SH with a maximum change of −0.3 mm/s on 30 Oct. 2003 near 88 km, 90°S (see Figure 3a). These changes were again modest compared with the background and amounted to about a 20% change in the upper polar SH mesosphere, primarily opposing the general upward motion at this time of year. The reduced upward motion thus resulted in a net adiabatic heating change (see Figure 3b), which led to a heating of the upper mesosphere that was discussed in section 3.

[26] A simulation was completed for the period 26 Oct. through 11 Dec. 2003 to study the longevity of the dynamical influence. We found that the perturbation to the atmosphere was fairly quickly damped such that over 90% of the impact of the Oct./Nov. 2003 SPEs was gone by 11 Dec. 2003. The majority of the mesospheric dynamical effects from SPEs diminish over a period of 4–6 weeks after the events. The maximum dynamical impacts appear to be confined to about 10 days near the big events.

[27] Could these computed changes in winds due to SPEs have significantly influenced the transport of constituents in Oct.–Dec. of 2003? This is an especially important question when focusing on the downward transport of NO_y created during SPEs, which has been shown to be an important factor in prolonging their influence [e.g., *Jackman et al.*, 2005a]. Although the vertical winds were computed to have been altered by the Oct./Nov. 2003 SPEs, the change did not significantly impact the downward transport of NO_y. The vertical winds were only changed by a maximum of about 20% and these changes diminished rapidly in the next few weeks.

5. Sensitivity Studies and Uncertainties

[28] We investigated the sensitivity of these results to the seasonal timing of the SPE and also the magnitude. The July 2000 (Bastille Day storm) SPE was similar in magnitude to the Oct./Nov. 2003 SPE. The computed dynamical changes for the July 2000 SPE were very similar to those reported here for the Oct./Nov. 2003 SPEs, however, the majority of the response was in the NH, the sunlit hemisphere. The bulk of the impact from SPEs is apparent in the sunlit hemisphere because of the very substantial impact on atmospheric heating/cooling from the ozone decreases.

[29] Since the dynamical effects of the Oct./Nov. 2003 SPEs were relatively modest, we performed a sensitivity study in which the proton flux was enhanced by a factor of 10. The purpose of this simulation was to determine the response of the atmosphere in a more perturbed state. We found that the temperature and wind effects were almost a factor of two larger in this very perturbed simulation implying that the SPE-induced mesospheric impact saturates. Since the majority of the mesospheric dynamical response is driven by the ozone depletion, the mesospheric effect is limited by the amount of ozone destruction, which is computed to be over 50% in the SH mesosphere.

[30] There are a large number of uncertainties in the model simulations including: 1) the magnitude of the input ionization rates for the protons; 2) possible latitudinal and longitudinal variations in the ionization rates, which are assumed to be uniform over the polar caps; 3) a relatively coarse 5 degree latitude-longitude and two grid point per scale height model, which will not simulate small scale structures; 4) uncertainties in the input photochemical reaction rates; and 5) uncertainties in the input of physical mechanisms (e.g., gravity waves). The TIME-GCM is continually being tested against measurements [e.g., *Roble*, 2000] and has been shown to represent the large-scale features of the mesosphere fairly well.

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